Copy 4

[redacted]

Copy

MEMO 5-15-59E

NASA MEMO 5-15-59E

GROUP 4
Downgraded at 3 year intervals; declassified after 12 years

[redacted]

NASA

COPY 2

MEMORANDUM

NASA MEMO 5-15-59E

EXPERIMENTAL EVALUATION OF SWIRL-CAN ELEMENTS FOR PROPANE-FUEL COMBUSTOR

By Eugene V. Pawlik and Robert E. Jones

Lewis Research Center
Cleveland, Ohio

THIS DOCUMENT RECLASSIFIED
TO Unclassified
AUTHORITY E.J. Oberg
BY REJ. DATE 2/71

CLASSIFIED DOCUMENT - TITLE UNCLASSIFIED

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON
June 1959

[redacted]

[redacted]

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MEMORANDUM 5-15-59E

EXPERIMENTAL EVALUATION OF SWIRL-CAN ELEMENTS FOR PROPANE-FUEL COMBUSTOR*

By Eugene V. Pawlik and Robert E. Jones

E-214

SUMMARY

The performance of swirl-can combustor elements for an experimental short-length turbojet combustor utilizing propane fuel was studied at high-altitude operating conditions. Fuel was injected into each element through tangential sonic orifices that created a swirling fuel-air mixture within each element. The elements varied from 1.0 to 3.0 inches in length and from 1.0 to 3.0 inches in diameter and served as combined fuel injectors and flame stabilizers. The individual elements operated stably at pressures as low as 6.5 inches of mercury absolute, with a reference velocity of 170 feet per second and an inlet air temperature of 80° F in a circular duct. Optimum performance was obtained with a 2-inch-diameter element having an orifice plate blocking about 55 percent of the inlet area.

A quarter-annulus combustor was constructed with elements that were nearly optimum as determined from single-element studies. This combustor gave a combustion efficiency of 95 percent at a reference velocity of 75 feet per second, a pressure of 14.7 inches of mercury absolute, an inlet temperature of 350° F, and a combustor length of 13.5 inches. In general, the blowout pressure of the arrays was found to be much higher than expected by the single-element stability data.

CT-1

INTRODUCTION

A previous report (ref. 1) describes a combustor that is short, light, and designed to perform satisfactorily over the operating conditions of advanced turbojets in supersonic flight. This combustor was composed of manifolded arrays of swirl-can elements. A swirl-can combustor element is a small conical can in which fuel and air are rapidly mixed and combustion is initiated. Combustors composed of swirl-can elements have the additional advantage of being easily scaled to larger sizes by this modular design approach. The combustion efficiency of

*Title, Unclassified.

[redacted]

this combustor was high (95 to 100 percent) at simulated supersonic test conditions, but varied from 85 to 90 percent at subsonic operating conditions. The temperature profiles were found to be acceptable, and the pressure loss was very low, about one-third that of present-day turbojet combustors. One serious drawback, however, is that the most promising swirl-can combustor blew out at total pressures below 14 inches of mercury absolute and exhibited intermittent blowout at pressures as high as 15 inches. The swirl-can elements were not optimized for flame stabilization with propane fuel. Improved stability would presumably increase combustion efficiency.

In order to improve performance at conditions corresponding to subsonic flight and to observe the relation between the operation of single combustor elements and combustor arrays, a research program was undertaken at the Lewis Research Center and is presented herein. In this program it was necessary to determine the effects of the inlet geometric variables of the individual swirl-can elements and their stability with propane fuel. The effects of fuel-tube location and swirl-can size were also determined. The results obtained indicated an optimum swirl-can size and geometry. Complete quarter-sector arrays of the most promising swirl-can types were tested to check the extent that the single-element data could be extrapolated. Combustion efficiency, total-pressure loss, and typical temperature profiles are shown for typical combustor arrays.

SYMBOLS

P	total pressure, in. Hg abs
P_i	combustor-inlet total pressure, in. Hg abs
T_i	combustor-inlet total temperature, $^{\circ}F$
V_{ref}	reference velocity, ft/sec
V_{ref}/P_iT_i	combustion parameter
η_B	combustion efficiency

APPARATUS

Installation

A schematic diagram of the combustor installation is shown in figure 1. This is essentially the same as used in reference 1. The fuel supply system was the same as used in reference 1 and is shown in figure 2.

The single-element test section as shown in figure 3 consisted of a circular duct with an inside diameter of $12\frac{3}{16}$ inches. An access door was situated such that individual combustor elements could be replaced through the side of the duct. The combustor element was mounted approximately in the center of the duct. A single spark wire discharged directly to the downstream edge of the swirl can provided ignition. The distance from the inlet of the swirl can to the exhaust instrumentation plane was approximately $12\frac{1}{2}$ inches.

The multielement test section was identical to that used in previous research described in reference 1.

Combustor Instrumentation

The single-element combustor instrumentation stations are shown in figure 3. At station 1, four bare-wire, Chromel-Alumel thermocouples, three static-pressure taps, and a total-pressure rake measured the combustor-inlet total temperature, static pressure, and total pressure, respectively. At station 2, combustor blowout was recorded from a total-recovery Chromel-Alumel thermocouple. At station 3, static pressure was measured at the wall taps, and a combined total-pressure and platinum-13-percent-rhodium - platinum aspirating-thermocouple probe in a polar-coordinate transversing mechanism (ref. 2) measured combustor-outlet total pressures and total temperatures. The probe moved circumferentially across the duct at five radial positions. A two-pen X-Y recording potentiometer connected to the survey system recorded outlet temperature.

The multielement combustor instrumentation is the same as has been used previously (ref. 1).

Combustor Elements

The operation of a typical swirl-can combustor element is illustrated schematically in figure 4. Fuel was injected from two simple orifices at sonic velocity tangential to the inner surface and approximately normal to the axis of the can. The tangential velocity of the fuel caused the fuel to spiral downstream along the walls of the can and mix rapidly with the air admitted through the inlet. Two fuel orifices are included in each can for ease in manifolding the cans together and for an improved fuel distribution. The inlet geometry and size of the swirl cans were varied as listed in tables I and II.

[redacted]

Combustor Arrays

Model 1. - This combustor consisted of an array of seven 3-inch-diameter elements arranged in two rows as shown in figures 5 and 6. Separate fuel-flow control was available for each row of elements as a means of controlling the temperature profile. Two different inlet orifices were tested on this model. Model 1a had inlet orifices with a $1\frac{1}{2}$-inch-diameter hole, while model 1b had inlet orifices with a $1\frac{1}{4}$-inch-diameter hole. The inlets are listed in table II as inlets E2 and E1, respectively.

Model 2. - This combustor was an array of 15 2-inch-diameter elements arranged in three rows as shown in figures 7 and 8. Three different inlet orifices were tested on this model. Model 2a had a 3/4-inch-diameter hole in the inlet orifice; model 2b had a 1-inch-diameter hole in the inlet; and model 2c had swirling-plate inlets (A9 of table I). This combustor also had separate fuel-flow control for each row of elements to adjust the temperature profile.

All the inlets used on models 1 and 2 are described in table III.

PROCEDURE

Blowout Determination

The performance of the swirl-can elements was investigated over a range of fuel flows at an inlet temperature of 80° F and an airflow of 2.2 pounds per second. The airflow was held constant while the pressure and velocity were varied. By this means, velocities up to 170 feet per second could be obtained as the pressure was gradually decreased to 6.5 inches of mercury absolute at blowout. A thermocouple mounted directly in the wake of the swirl can was used to indicate blowout. Blowout limits are reported in terms of the severity factor at blowout ($V_{bo}/P_{bo}T_i$). Parameters of the type $P^{1.5}T/V$ (ref. 3) or V/PT (ref. 4) have been used by other investigators to establish approximate criteria for combustor blowout.

Quarter-Sector Combustor Operating Conditions

The performance of the swirl-can combustor arrays was investigated over a range of fuel-air ratios at the following inlet air conditions:

[redacted]

Total pressure, $P_{t,in}$, in. Hg abs	Airflow rate for quarter sector, lb/sec	Total temperature, $T_{t,in}$, $^{\circ}F$	Reference velocity, V_{ref}, ft/sec (a)	Severity factor, $\frac{V_{ref}}{P_{t,in}T_{t,in}}$, (cu ft)(sec)/(lb)($^{\circ}R$)
10.0	0.897	350	75	13.1×10^{-5}
12.0	1.068			10.9
14.0	1.256			9.36
14.7	1.32			8.92
20.0	1.795			6.55

[a]Based on combustor max. cross-sectional area of 0.73 sq ft (quarter sector) and combustor-inlet air density.

Combustion Efficiency

Combustion efficiency was not calculated for the individual combustor elements since it would be difficult to obtain any degree of accuracy in view of the mass-weighting problem involved. Combustion efficiency for the arrays was calculated as the percentage ratio of actual to theoretical increase in enthalpy from the combustor-inlet instrumentation plane to the combustor-outlet traversing plane. A value of 19,930 Btu per pound was used for the lower heat of combustion of propane.

RESULTS

A summary of the combustion performance characteristics of the different combustor elements investigated with propane fuel is presented in table I. A brief description of the design modifications made and the purpose of the modifications are noted in the table. The performance of each element is reported in table I in terms of (1) blowout severity factor $(V_{bo}/P_{bo}T_i)$, (2) minimum blowout pressure in inches of mercury absolute, (3) fuel flow at minimum blowout in pounds per hour, and (4) comments on the operation of the elements based on visual observation.

Combustor Blowout

Stable operation was obtained with a simple conical-shell element (model A0) only at relatively high pressure. As inlet blockage was increased, the stability defined by the blowout severity limit $(V_{bo}/P_{bo}T_i)$ generally increased. Thus, models A1, A2, and A3 had a high percentage of inlet blockage. The inlet air was broken up into a large number of small streams to create a high turbulence level within the elements. Since good results were obtained at low fuel flows, the inlet was streamlined (model A4) to improve the pressure-drop characteristics of the elements. Decreased blockage and a variation in inlet geometry (models A5, A6, and A7) were investigated to extend the stability limit at higher fuel flows. Improved operation at higher fuel flows was obtained by increasing the turbulence level within the element by an inlet that imparted a swirling motion to the incoming airstream (models A8 and A9), but the stability at the low fuel flows was no longer satisfactory. Model A9 represents a unique design since the stability improved considerably with increasing fuel flow. Simpler geometric configurations such as truncated cones, nozzles, and orifices were tested (models A10, A11, A12, and A13) to find an inlet not as sensitive to fuel-flow variations. Model A13, which consisted of a simple inlet orifice, proved to be mildly sensitive to fuel flows over the range tested. The effect of the inlet diameter of this configuration was observed in order to optimize the stability characteristics. These results are shown in figure 9 as blowout pressure plotted against percent blocked inlet area for various fuel flows. Lowest blowout pressures and greatest insensitivity to fuel-air ratio were obtained by using an orifice plate inlet with a blockage of 55 percent. Fuel flow in pounds per hour plotted against blowout pressure in inches of mercury absolute for the best elements and several contrasting poorer ones is shown in figure 10.

Since the best stability performance was obtained with an inlet area blockage of 55 percent, element sizes from $1\frac{1}{2}$ to 3 inches in diameter containing simple inlet orifices were tested to determine if the optimum ratio generally applied to all element sizes. The blowout performance of each element is reported in table II. Generally, element stability increased with increasing element diameter. In addition, it was determined that the axial location of the fuel injector had little influence on combustion stability over the range of positions investigated. When the injector was located near the downstream end of the element, however, the fuel holes were drilled at an angle of 40° upstream of the normal to increase the residence time of the fuel in the element.

Outlet Temperature Distribution

A typical temperature profile of a combustor element (model A17) is shown in figure 11. This profile was obtained from the temperature survey probe located about 12 inches from the element as shown in figure 3. The fuel flow is 10.66 pounds per hour at a reference velocity of 108.8 feet per second, a reference pressure of 10.3 inches of mercury absolute, and an inlet temperature of 80° F.

Performance of Multielement Combustors

Multielement combustors (figs. 6 and 8) consisting of 7 and 15 elements were constructed with two and three rows of cans, respectively. These combustors were mounted in a quarter sector of an annular housing and tested with various inlets. Each element had its own fuel injector supplied from a common manifold. A summary of the results obtained in the investigation of multielement combustors is presented in table IV.

Brief tests were conducted with these combustors to demonstrate the feasibility of the multielement array. Combustion efficiencies were determined with propane (figs. 12 and 13) at a reference velocity of 75 feet per second, an inlet total pressure of 10 to 20 inches of mercury absolute, and an inlet total temperature of 350° F. At a pressure of 14.7 inches of mercury absolute, the combustion efficiency of the best combustor, model 2a, varied from 85 to 95 percent.

Figure 14 shows some typical combustor-outlet average radial temperature profiles for all the test combustors. The profile for model 2c demonstrates the control afforded when the fuel flow to the individual rows of combustion elements can be adjusted.

Figure 15 shows the total-pressure loss in percent of inlet total pressure for both models. At total-temperature ratios from 1.6 to 2.8, the pressure varied between 1.3 and 2.6 percent for both combustors.

DISCUSSION

Single Combustor Element Tests

Of the several geometric variables investigated, the amount of blockage at the combustor element inlet had the largest effect on element stability. Best results were obtained with a 1-inch-diameter orifice having an inlet area blockage of 55 percent (inlet A13, table I) as shown in figure 9. Optimum performance was virtually independent of the fuel-flow rate. The orifice plate inlet was selected both for the high performance obtained and for simplicity in construction. As shown in table II, the small elements ($1\frac{1}{2}$ to $1\frac{3}{4}$ in. in diam.) generally had higher blowout pressures than did the larger elements (2 to 3 in. in diam.). However, small-diameter elements are preferable for combustor work in that better temperature profiles can be obtained in a short length with many small heat sources than with a few large sources. The 2-inch-diameter elements represent a compromise between combustion stability and temperature profile.

[redacted]

The effect of the fuel-tube location was briefly studied. Very little effect on the minimum blowout pressure was noted when the fuel-tube location was kept near the midpoint of the can axis. However, if the fuel tube was too near the can inlet or exit, the minimum blowout pressure would be increased.

The outlet temperature distribution of can A17 is shown in figure 11 as measured $10\frac{1}{2}$ inches downstream of the can exit. This profile may be considered typical of all swirl cans. If the mixing length is held constant, $10\frac{1}{2}$ inches in this case, a smaller but more uniform profile results from smaller combustor elements. Thus, the use of many small elements offers the possibility of very short combustors with acceptable gas temperature profiles. The use of fewer but larger elements would probably require a longer combustor to achieve a similarly uniform temperature profile.

Combustor Arrays

The combustion stability of models 1a and 1b (fig. 12) was considerably less than expected from the single element studies. Intermittent blowout occurred frequently though the cans would generally relight in a few seconds. The inlet orifice diameter of these elements was reduced to $1\frac{1}{4}$ inches (model 1b) in an attempt to improve the element stability, but with little success. Besides, average radial temperature profiles for models 1a and 1b as shown in figure 14 were too unacceptable to merit further work on this combustor.

The performance of model 2 (fig. 13) was somewhat improved over that of model 1. However, intermittent blowout was still prevalent at low pressures, 14 inches of mercury absolute and below. Increasing the inlet orifice diameter from 3/4 inch (model 2a) to 1 inch (model 2b), the optimum diameter as determined by individual element studies, increased the intermittent blowout tendency. Model 2b was so sensitive to pressure that only one datum point could be obtained at a pressure of 14.7 inches of mercury absolute.

In view of the poor operational characteristics of this combustor with orifice-type inlets, another inlet type (A9) was tried. This inlet also gave good results on single combustor elements (fig. 10) but did not improve the operation of the combustor (model 2c, fig. 13). At a pressure of 20 inches of mercury absolute, the combustor would not operate below a fuel-air ratio of 0.0135. Also, intermittent blowout persisted until a fuel-air ratio of approximately 0.015 was reached.

[redacted]

At a pressure of 14.7 inches of mercury absolute, model 2a showed a slight gain in combustion efficiency over model 1 of reference 1. This gain in efficiency was about 4 percent at a fuel-air ratio of 0.016. Lower pressure performance was also considerably improved as model 2a operated stably to pressures as low as 10 inches of mercury absolute.

The average radial temperature profiles for models 1a and 1b were unsatisfactory and could not be improved very much by proportioning the fuel flow between the two rows of cans. Circumferential profiles also exhibited gradients too steep to be acceptable. The average radial temperature profiles for models 2a and 2b were also unacceptable. However, proportioning of the fuel flow between the three rows of cans was very effective in controlling the profile, and such a controlled profile is shown for model 2c (fig. 14). Because smaller combustor elements were used in model 2, circumferential temperature profiles exhibited fewer and less sharp temperature gradients and were considered tolerable.

The total-pressure loss of models 1 and 2 was approximately 2 percent of the inlet total pressure, which is roughly one-half that of present-day combustors.

SUMMARY OF RESULTS

The following results were obtained in an investigation of individual swirl-can combustor elements with propane fuel:

1. Stable combustion was obtained at a reference velocity as high as 170 feet per second, a pressure of 6.5 inches of mercury absolute, and an inlet temperature of 80° F.

2. Stability was strongly affected by the geometry of the element inlet. A simple orifice plate mounted on a 2-inch-diameter conical element with an optimum inlet blockage of 55 percent was among the most stable.

3. Reducing element size below 2 inches in diameter reduced stability. Element sizes from 2 to 3 inches in diameter were found to give satisfactory performance results down to 7 inches of mercury absolute.

The following results were obtained in an investigation of two swirl-can combustors consisting of 2- and 3-inch-diameter elements in a quarter-sector duct:

1. The stability of the arrays was markedly inferior to that predicted from results of the single-element studies. Combustor blowout often occurred at pressure as high as 20 inches of mercury absolute and velocities as low as 75 feet per second.

2. With the 2-inch-diameter element having a 3/4-inch-diameter inlet orifice, combustion efficiencies near 95 percent were attained at a reference velocity of 75 feet per second, a pressure of 14.7 inches of mercury absolute, an inlet temperature of 350° F, and a combustor length of 13.5 inches. An individual element of this type operated stably to velocities as high as 130 feet per second at the same air pressure and an inlet air temperature of 80° F.

3. Temperature profiles for the combustor consisting of 15 2-inch-diameter elements were adjusted by proportioning the flow to each row of elements and were considered acceptable.

E-214

4. Total-pressure loss in percent of inlet total pressure varied approximately from 1.3 to 2.6 percent as total-temperature ratios varied from 1.6 to 2.8 for both combustors at inlet total pressures from 10 to 20 inches of mercury absolute, a reference velocity of 75 feet per second, and an inlet air temperature of 350° F.

CONCLUDING REMARKS

Multielement swirl-can combustors can be made to maintain combustion at low total pressure and temperatures, corresponding to high-altitude subsonic flight, but with reduced combustion efficiency. Stability demonstrated by individual swirl cans could not be achieved with a combustor array of identical swirl cans.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 26, 1959

REFERENCES

1. Jones, R. E., and Pawlik, E. V.: A Preliminary Investigation of the Performance of a Short-Length Turbojet Combustor Using Vaporized Hydrocarbon Fuels. NACA RM E57J03, 1958.

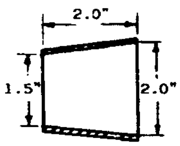
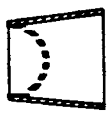
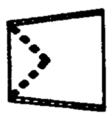
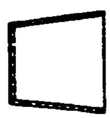
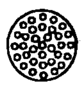
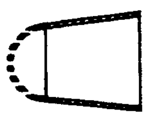
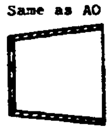
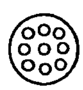
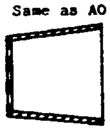
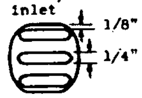
2. Friedman, Robert, and Carlson, Edward R.: A Polar-Coordinate Survey Method for Determining Jet-Engine Combustion-Chamber Performance. NACA TN 3566, 1955.

3. Schirmer, R. M., Kittredge, G. D., and Fromm, E. H.: Evaluation of Fuel Characteristics in Thermojet Engine Combustion Processes. Summary Rep. No. 403-19-52R, Phillips Petroleum Co., Jan. 1953. (Navy Contract NOas 52-132-C.)

4. Norgren, Carl T., and Childs, J. Howard: Effect of Fuel Injectors and Liner Design on Performance of an Annular Turbojet Combustor with Vapor Fuel. NACA RM E53B04, 1953.

[redacted]

TABLE I. - SUMMARY OF DATA FOR INDIVIDUAL COMBUSTOR 2-INCH ELEMENTS WITH PROPANE FUEL

Model	Description and sketch of configuration	Inlet description	Purpose of modification	Blowout severity factor, $\times 10^5$	Minimum blowout pressure, in. Hg abs	Fuel flow at minimum blowout, lb/hr	Comments on combustor element operation
A0	Basic conical shell 	No inlet	Original swirl can	12.2	14.7	13	Very poor stability
A1	Same as A0 	Semispherical inlet; 20 3/32"-diam. holes; 16 1/8"-diam. holes;  drilled hole area, 0.334 sq in.; holes drilled parallel to airstream	Airstream blocked and broken into small streams to increase stability	34.5	5.9	10	Stability good at low fuel flow, sensitive to fuel flow
A2	Same as A0 	Cone inlet holes drilled at right angles; 39 3/32"-diam. holes;  drilled hole area, 0.269 sq in.; projected hole area, 0.108 sq in.	Different method of small-stream introduction tried to eliminate fuel-flow sensitivity	36.1	6.9	10	Stability fair at low fuel flow, sensitive to fuel flow
A3	Same as A0 	Flat-plate inlet; 34 1/8"-diam. holes; inlet area, 0.417 sq in. 	Alternate method of small-stream introduction altered to eliminate fuel-flow sensitivity	36.8	5.8	10	Stability good at low fuel flow, sensitive to fuel flow
A4	Same as A0 	Semispherical inlet; 28 3/32"-diam. holes; drilled hole area,  0.193 sq in.; holes drilled parallel to airstream	Alternate method of small-stream introduction altered to eliminate fuel-flow sensitivity. Possible low-pressure-drop characteristics anticipated	16.0	11.7	10	Stability poor
A5	Same as A0 	Flat-plate inlet;  9 1/4"-diam. holes; inlet area, 0.442 sq in.	Less severe methods of airstream breakup were used in order to improve stability	24.4	6.5	10	Stability good at low fuel flows, very sensitive to fuel flow
A6	Same as A0 	Flat-plate slotted inlet  3 1/4"-wide slots; inlet area, 0.85 sq in.	Same as for A5	32.2	7.7	10	Stability good at high fuel flows, sensitive to fuel flow

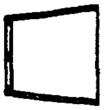
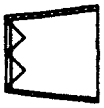
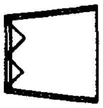
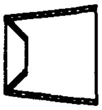
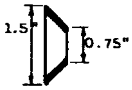
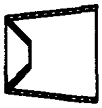
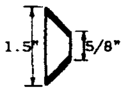
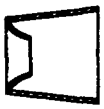
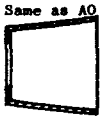
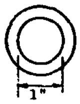
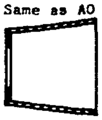
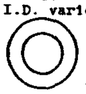
[redacted]

E-214

CT-2 back

[redacted]

TABLE I. - Concluded. SUMMARY OF DATA FOR INDIVIDUAL COMBUSTOR 2-INCH ELEMENTS WITH PROPANE FUEL

Model	Description and sketch of configuration	Inlet description	Purpose of modification	Blowout severity factor, ×10^5	Minimum blowout pressure, in. Hg abs	Fuel flow at minimum blowout, lb/hr	Comments on combustor element operation
A7	Same as A0 	Flat-plate inlet  Inlet area, 0.45 sq in.	Same as for A5	32.2	6.0	10	Stability good at low fuel flows, extremely sensitive to fuel flow
A8	Same as A0 	Swirl-type inlet, eight blades at 45° angle  Inlet area, 0.45 sq in.	Swirling method of air-stream mixing investigated; the direction imparted to the air swirl is opposite to the direction of fuel swirl	19.6	8.7	10	Stability fair at low fuel flows, fairly sensitive to fuel flow
A9	Same as A0 	Swirl-type inlet Same as A8 inlet	Same as A8, except the direction of fuel swirl is the same as that of the air	60.0	6.1	20	Stability good at high fuel flows, not too sensitive to fuel flows
A10	Same as A0 	Truncated-cone inlet  Inlet area, 0.442 sq in.	Single air-stream approach used to improve stability	21.0	9.5	20	Stability poor, decreases as fuel flow increases
A11	Same as A0 	Truncated-cone inlet  Inlet area, 0.307 sq in.	Slight modification of A10	17.0	10.3	10	Stability poor
A12	Same as A0 	Nozzle inlet  Inlet area, 0.594 sq in.	Same as A10	33.5	7.5	10	Stability fair at low fuel flow, fairly sensitive to fuel flow
A13	Same as A0 	Orifice inlet  Inlet area, 0.786 sq in.	Same as A10	66.2	6.5	15.5	Stability good, mildly sensitive to fuel flow over range tested
A14 to A17	Same as A0 	Orifice inlets I.D. varied from  1/2" to $1\frac{1}{4}$"; inlet area varied from 0.196 to 1.228 sq in.	Effect of inner diameter on an operation studied to determine optimum size				See fig. 9

[redacted]

E-214

TABLE II. - SUMMARY OF DATA FOR INDIVIDUAL

COMBUSTOR ELEMENT SIZE STUDY

Model	Element size	Orifice diameter size, in.	Blowout severity factor, $\times 10^5$	Minimum blowout pressure, in. Hg abs	Fuel flow at minimum blowout, lb/hr
B1	1.5	5/8	16.6	12.9	5.0
B2		3/4	21.2	11.4	6.5
B3		7/8	47.8	7.6	10.0
C1	1.75	3/4	37.3	8.6	6.0
C2		7/8	42.8	8.1	5.0
C3		1	51.9	7.3	6.0
D1	2.5	$1\frac{1}{8}$	40.0	8.3	10.0
D2		$1\frac{1}{4}$	39.1	8.4	10.0
D3		$1\frac{3}{8}$	82.0	5.8	13.0
E1	3.0	$1\frac{1}{4}$	65.4	6.6	10.0
E2		$1\frac{1}{2}$	74.2	6.2	10.0
E3		$1\frac{3}{4}$	67.4	6.5	15.0

[redacted]

E-214

TABLE III. - ARRAY MODELS AND ELEMENT DESCRIPTION

Model number	Element size, in.	Number of elements	Inlet
1a	3	7	$1\frac{1}{2}$-in.-diam. orifice
1b	3	7	$1\frac{1}{4}$-in.-diam. orifice
2a	2	15	3/4-in.-diam. orifice
2b	2	15	1-in.-diam. orifice
2c	2	15	Swirlers same as on model A9

[redacted]

TABLE IV. - EXPERIMENTAL DATA

Run	Combustor-inlet total pressure, in. Hg abs	Combustor-inlet temperature, °F	Air-flow rate, lb/sec	Combustor reference velocity, ft/sec	Fuel-flow rate, lb/hr	Fuel-air ratio	Mean combustor-outlet temperature, °F	Combustion efficiency	Total-temperature ratio	Total-pressure loss, $\Delta P/P_1$	Element inlet
Model 1											
1	10.0	350	0.895	75.0	67.99	0.0211	1362	66.7	2.25	2.21	$1\frac{1}{2}$-in.-diam. orifice
2					74.59	.0232	1411	64.3	2.31	2.28	
3					61.81	.0192	1273	66.3	2.14	2.14	
4					82.79	.0257	1461	61.3	2.38	2.51	
5	14.0		1.248	74.7	50.97	.0183	995	75.6	1.67	1.63	
6					82.14	.0222	1302	71.5	2.18	1.89	
7					99.94	.0257	1483	70.4	2.40	2.06	
8	10.0		0.879	73.7	50.69	.0160	1217	73.4	2.07	2.06	$1\frac{1}{4}$-in.-diam. orifice
9	10.0		.879	73.7	66.83	.0211	1335	64.8	2.22	2.14	
10	14.0		1.272	76.2	66.52	.0145	1162	75.5	2.00	2.66	
11	14.0		1.272	76.2	83.06	.0180	1328	74.4	2.21	2.76	
Model 2											
12	10.0	350	0.891	74.7	33.94	0.0106	964	76.3	1.76	1.70	3/4-in.-diam. orifice
13					44.59	.0139	1122	74.7	1.95	1.84	
14					65.25	.0203	1298	64.4	2.17	1.92	
15					80.82	.0252	1479	63.5	2.39	2.06	
16	14.7		1.299	74.1	72.77	.0156	1422	94.5	2.32	1.78	
17					88.38	.0189	1611	93.1	2.56	1.85	
18					61.66	.0132	1216	88.6	2.07	----	
19	20.0		1.879	78.8	97.21	.0144	1408	100.3	2.30	1.75	
20					85.52	.0126	1286	100.0	2.16	1.31	
21					60.40	.0089	1019	98.9	1.82	----	
22	14.0		1.259	75.4	110.69	.0244	1775	83.7	2.76	2.00	1-in.-diam. orifice
23	20.0		2.079	86.8	145.08	.0195	1536	85.1	2.46	2.18	
24					103.40	.0138	1175	80.4	2.02	1.88	
25					147.34	.0198	1593	94.1	2.53	2.23	
26	14.7		1.400	79.8	120.11	.0233	1537	72.2	2.46	2.50	Swirling plate
27					97.32	.0193	1270	65.7	2.14	2.58	
28					62.67	.0125	1023	71.9	1.83	1.86	
29					97.76	.0194	1261	64.6	2.13	2.03	
30	20.0		1.855	77.8	151.34	.0225	1688	84.6	2.65	2.10	
31					107.06	.0160	1122	65.2	1.95	1.62	
32					92.81	.0139	838	46.6	1.60	1.51	
33					122.84	.0184	1358	75.7	2.24	1.81	

[redacted]

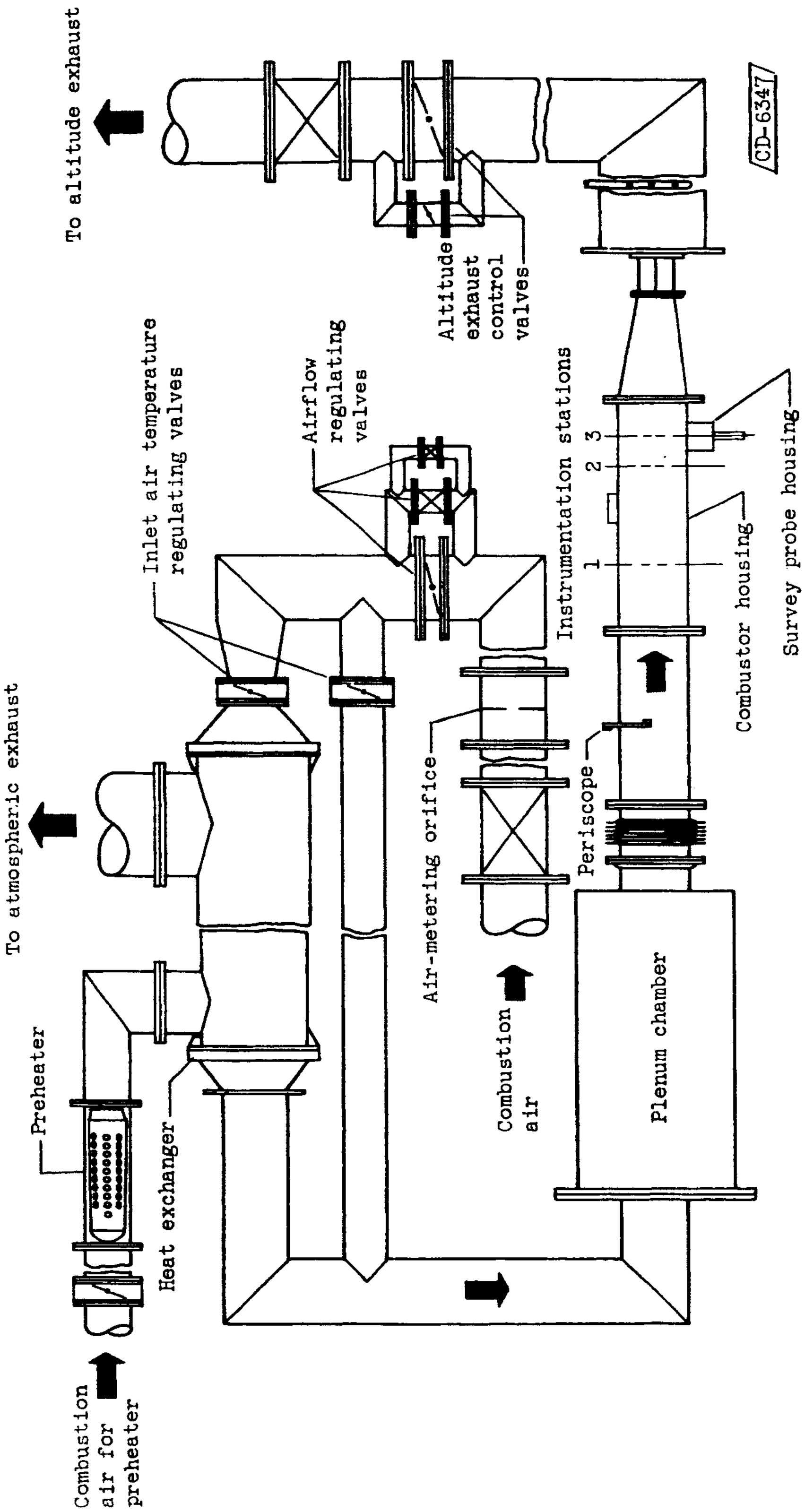


Figure 1. - Installation of test section for investigation of combustor elements.

[redacted]

[redacted]

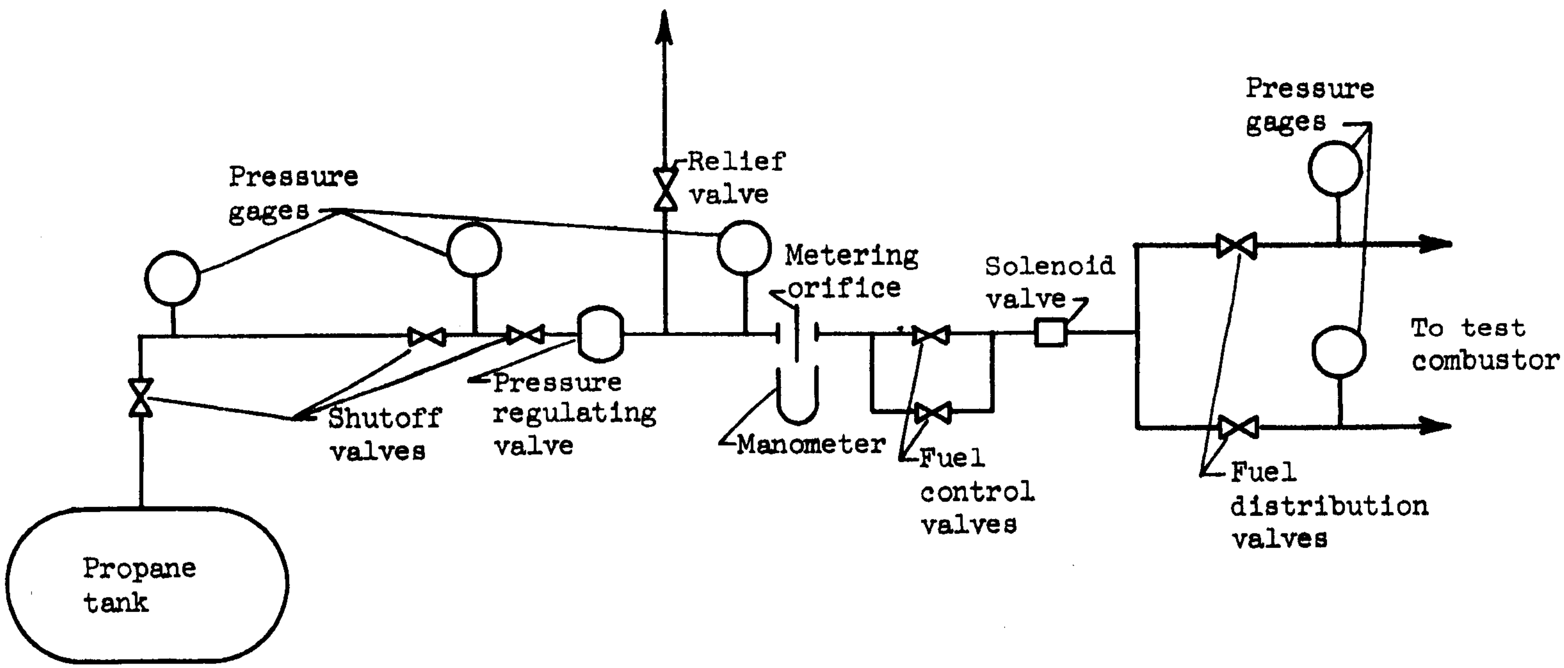
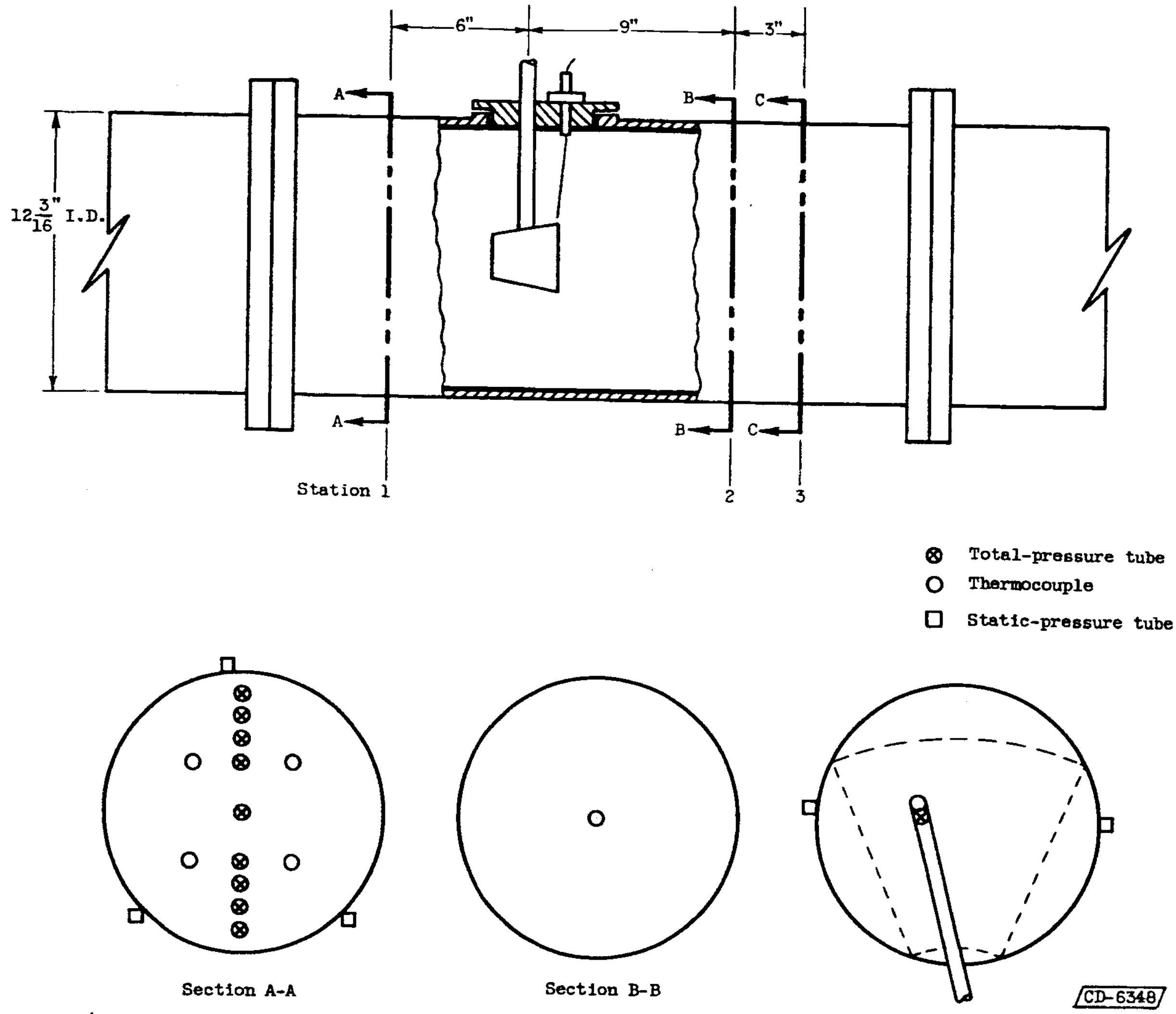


Figure 2. - Propane-fuel system.

[redacted]

[redacted]



Section A-A
(Combustor-inlet total-pressure tubes, thermocouples, static-pressure tubes)

Section B-B
(Combustor-outlet thermocouples)

Section C-C
(Combustor-outlet static-pressure tubes, thermocouple, and total-pressure tube on sweeping probe)

Figure 3. - Combustor element installation showing location of temperature and pressure measuring instruments in instrumentation planes.

[redacted]

E-214

CT-3 back

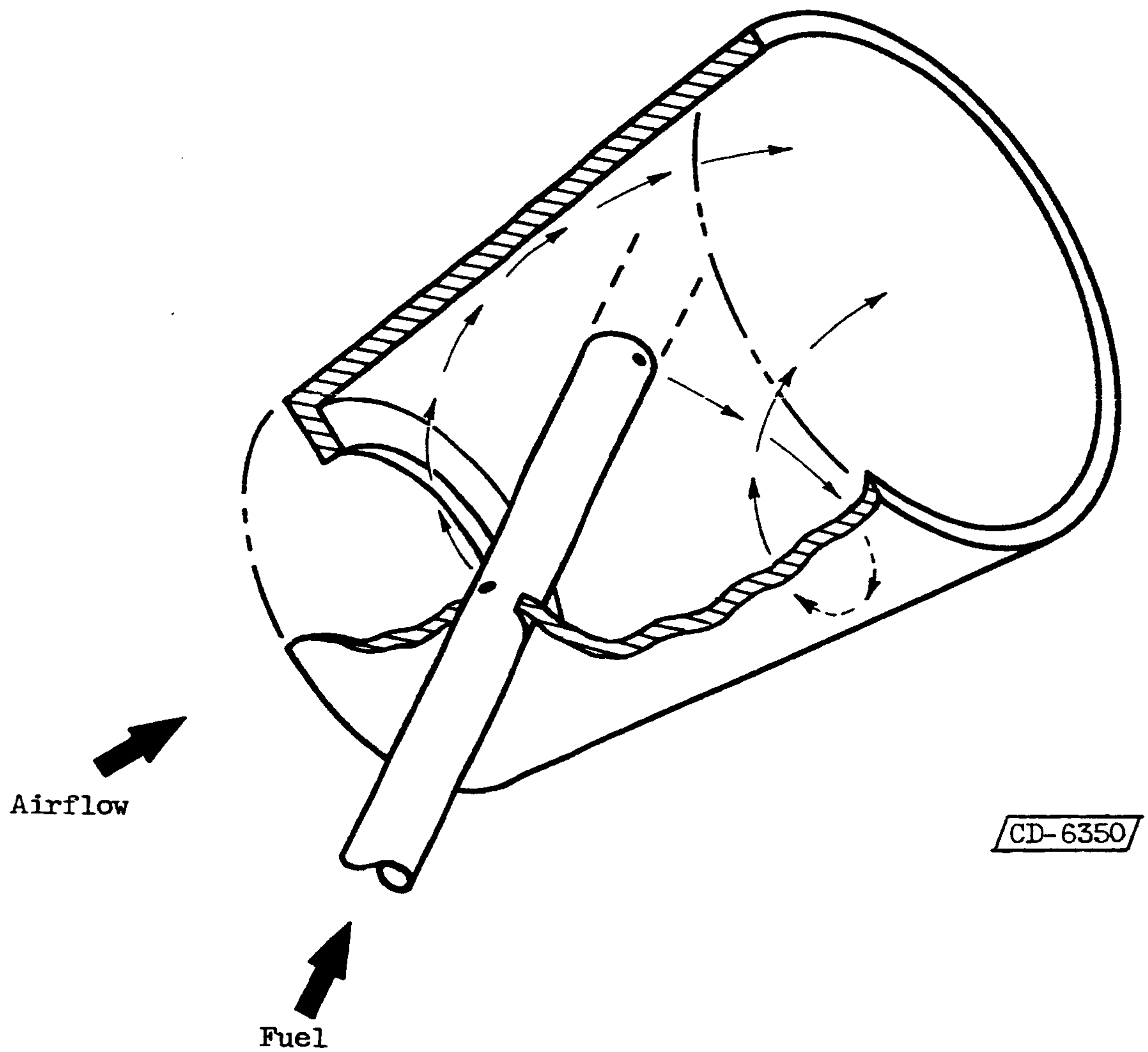


Figure 4. - Operation of typical swirl-can combustor element (model A13).

E-214

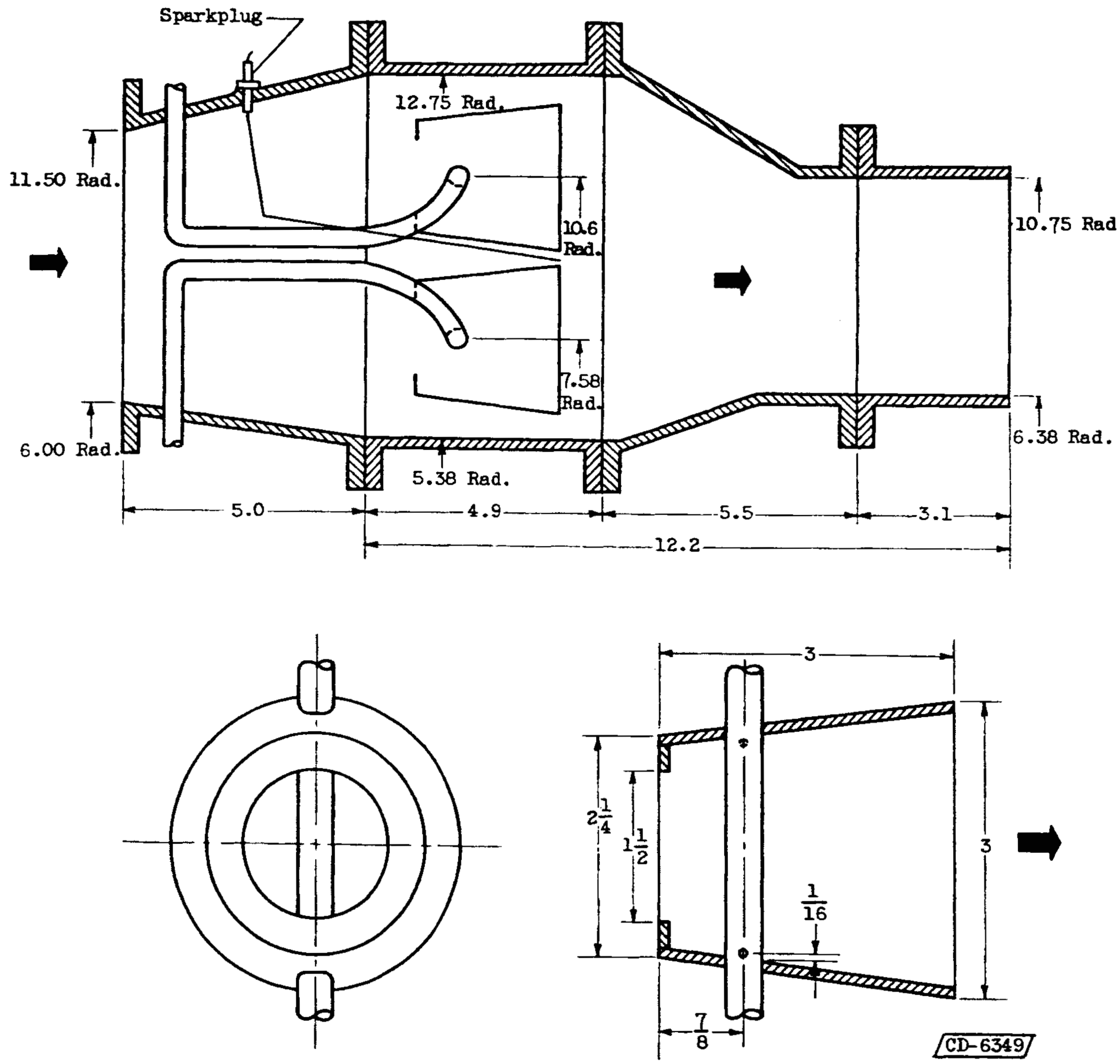


Figure 5. - Cross section of model 1a mounted in one-quarter-sector annular housing. (All dimensions in inches.)

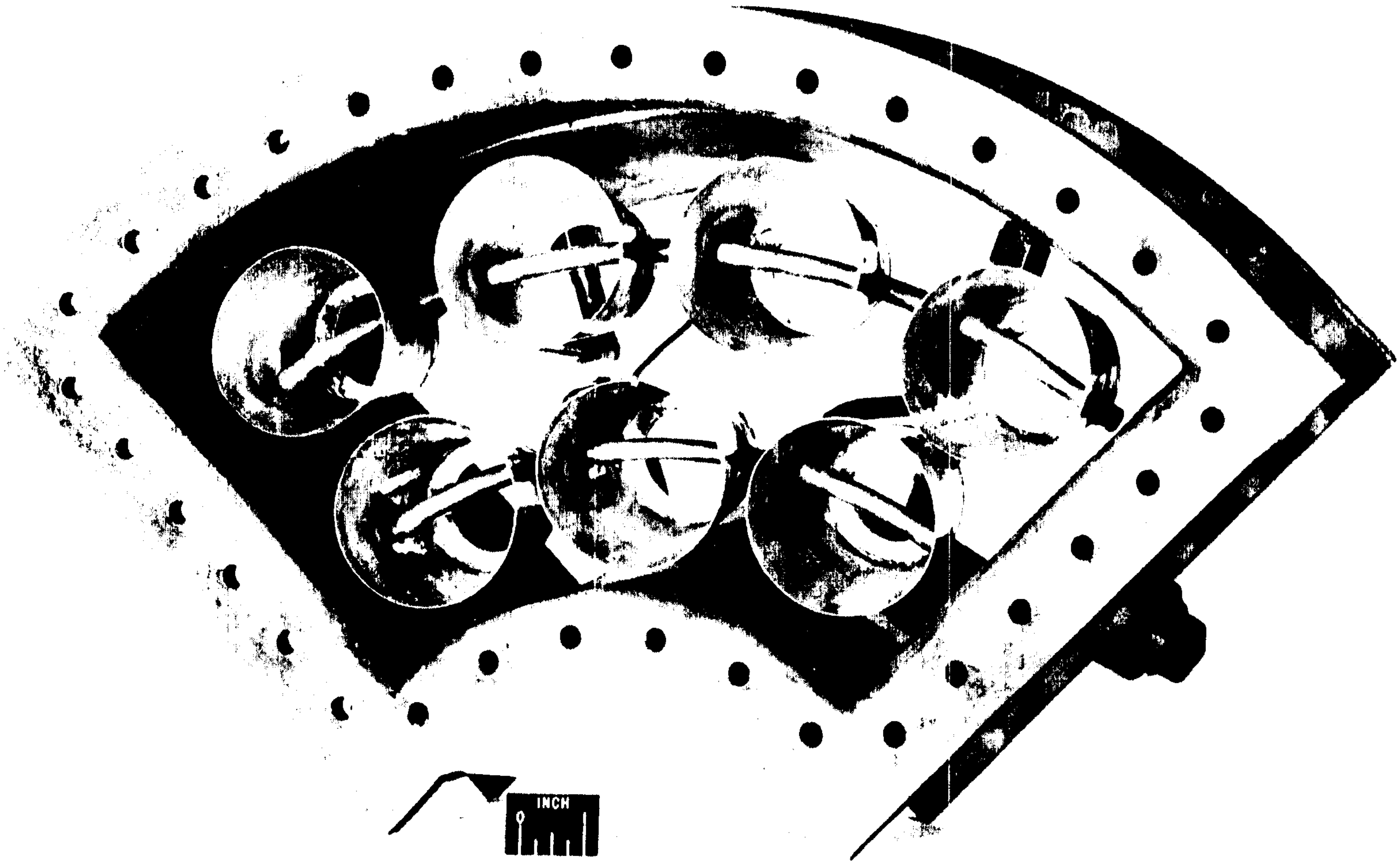


Figure 6. - Quarter-annulus combustor composed of an array of model E2 combustor elements.

[redacted]

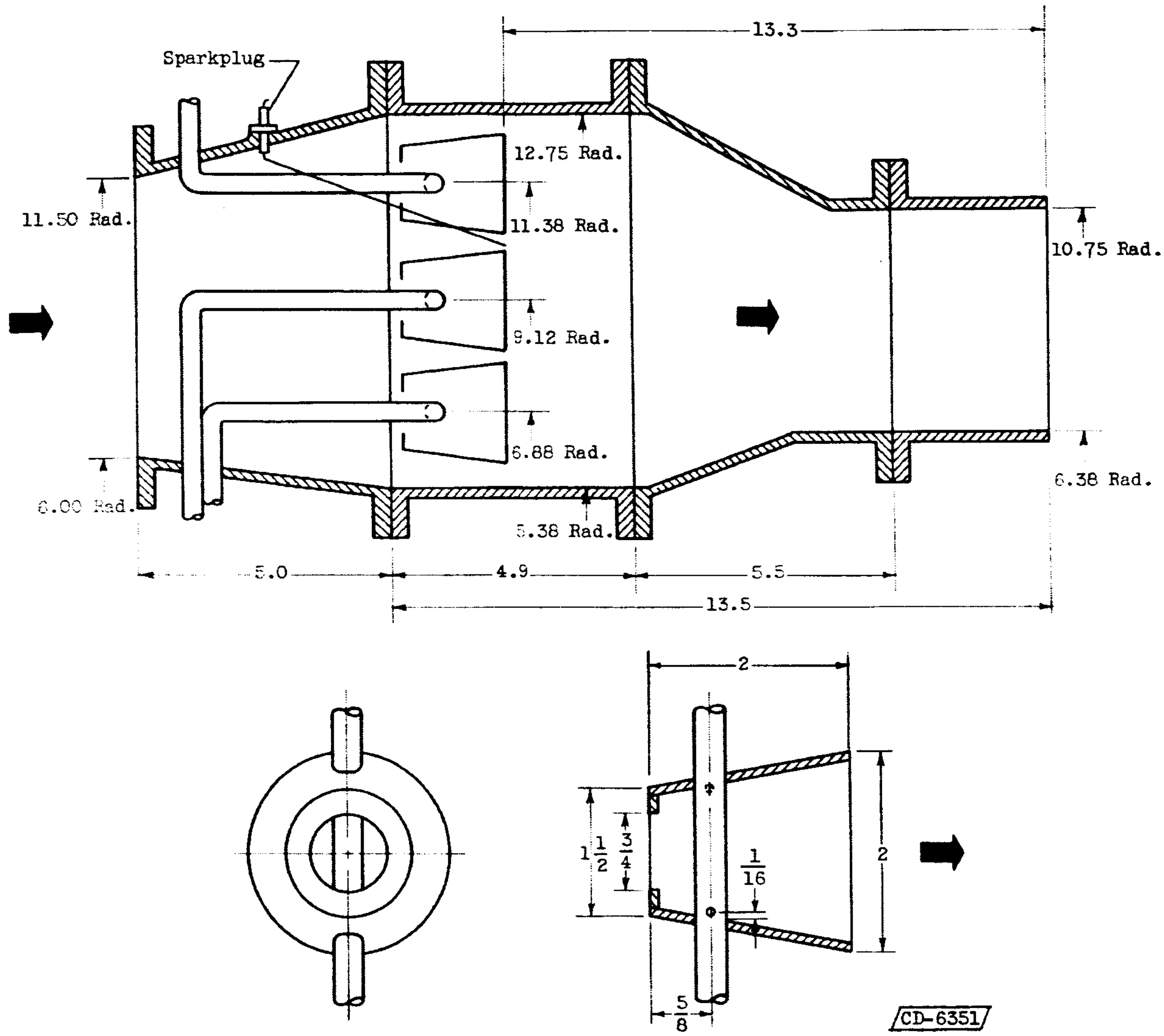
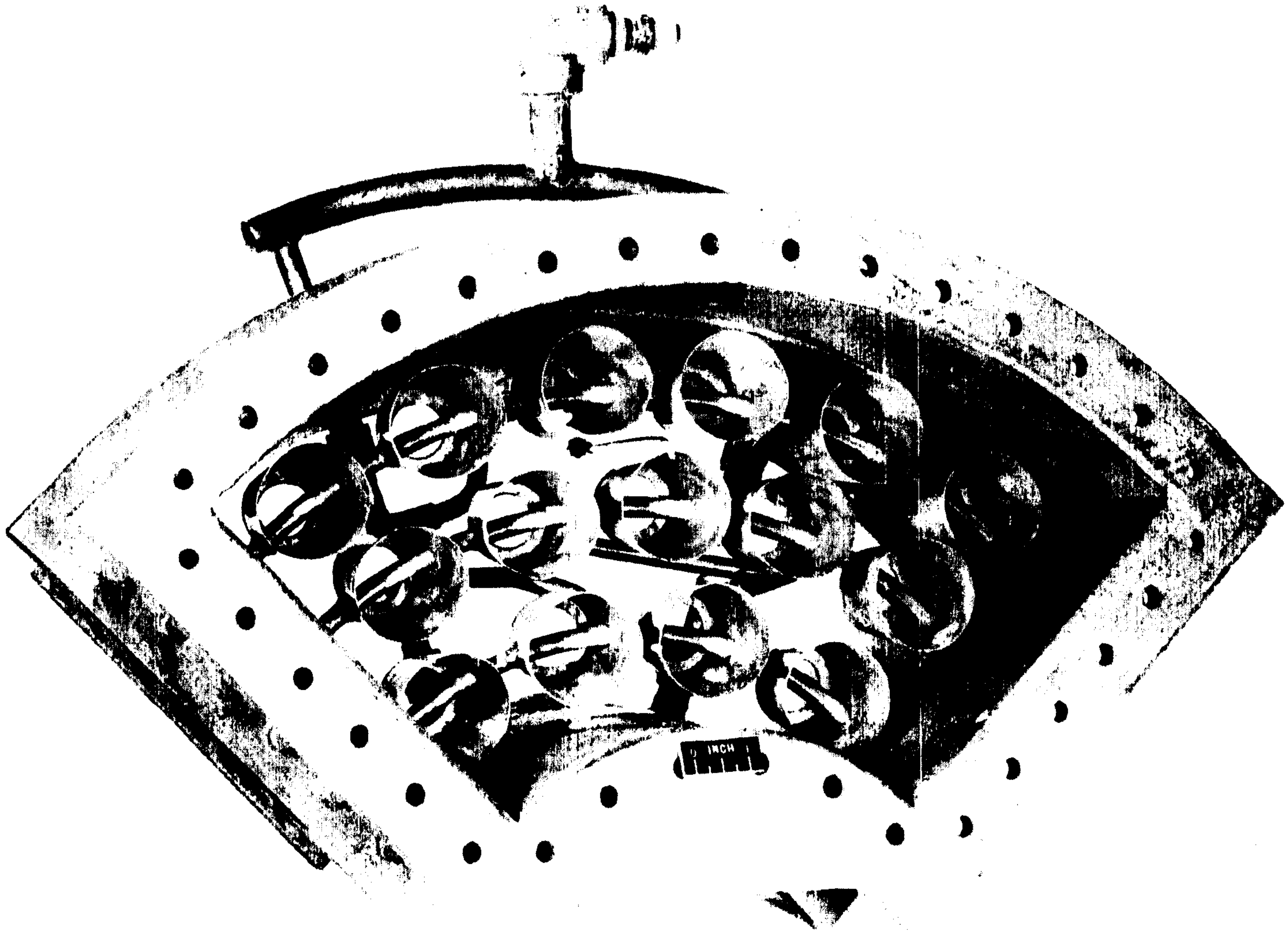


Figure 7. - Cross section of model 2a mounted in one-quarter-sector annular housing. (All dimensions in inches.)

[redacted]

[redacted]



C-47185

Figure 8. - Quarter-annulus combustor composed of an array of model A16 combustor elements.

[redacted]

[redacted]

[redacted]

[redacted]

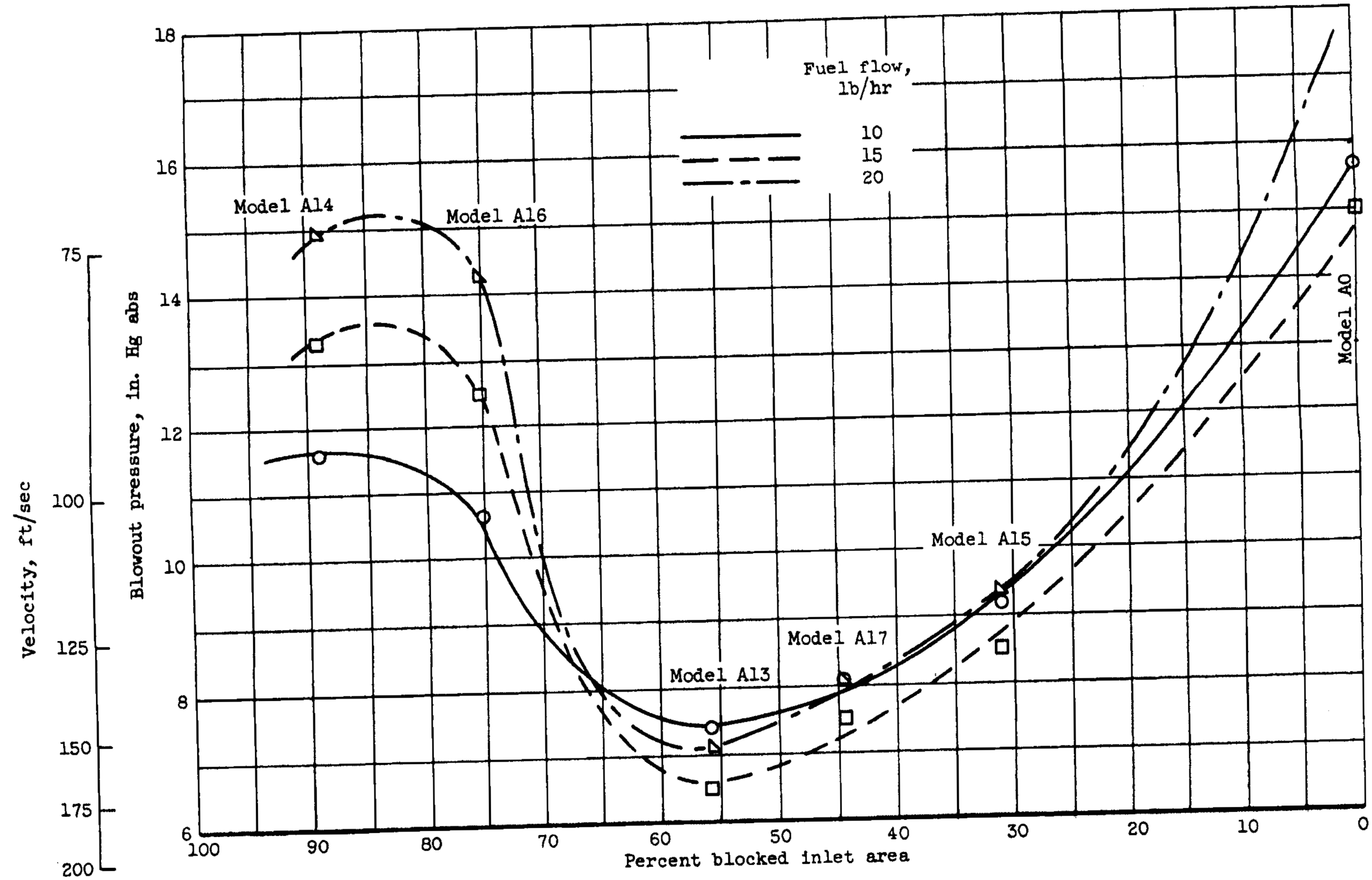


Figure 9. - Optimum orifice size determination. Inlet air temperature, 80° F.

[redacted]

[redacted]

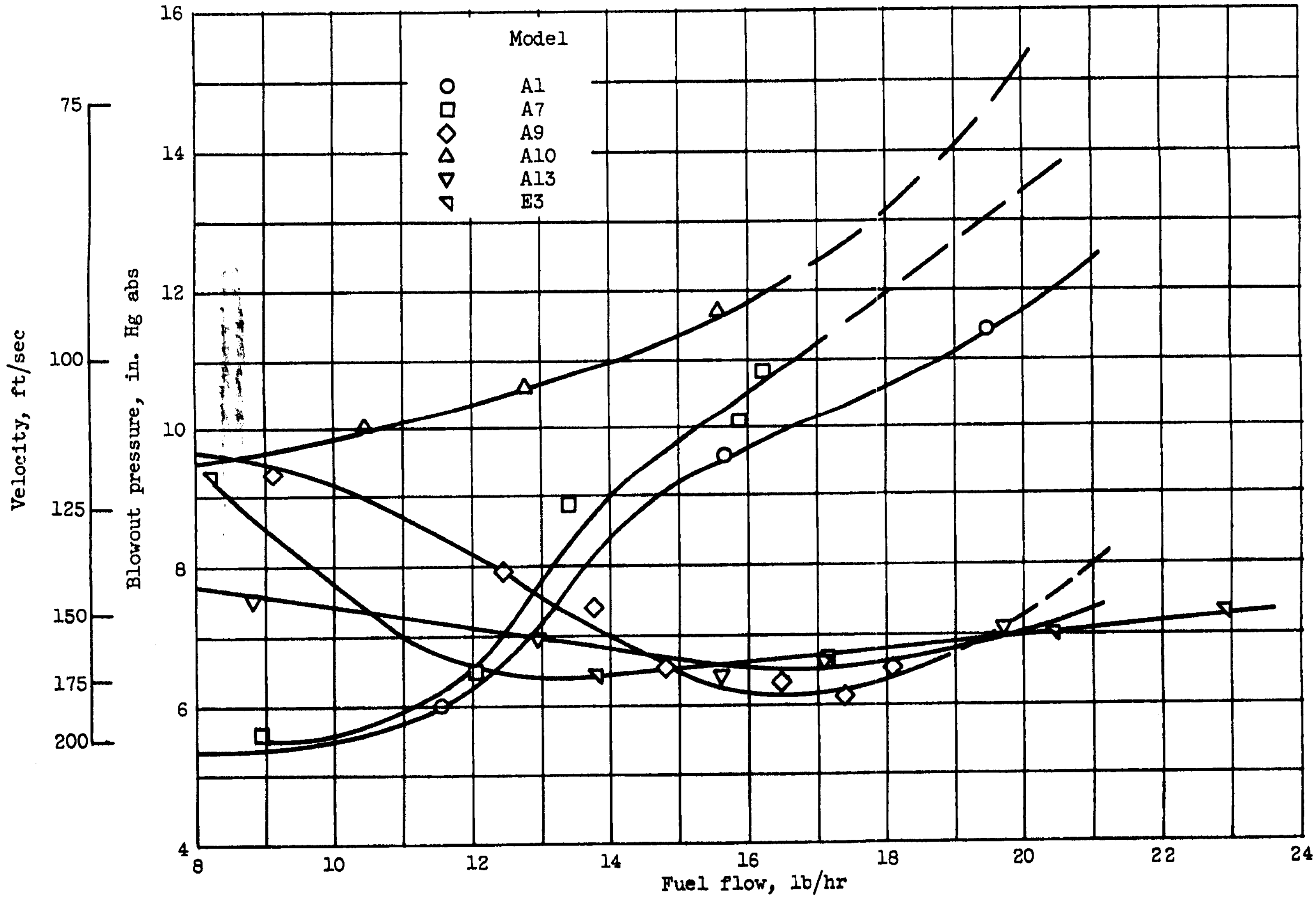
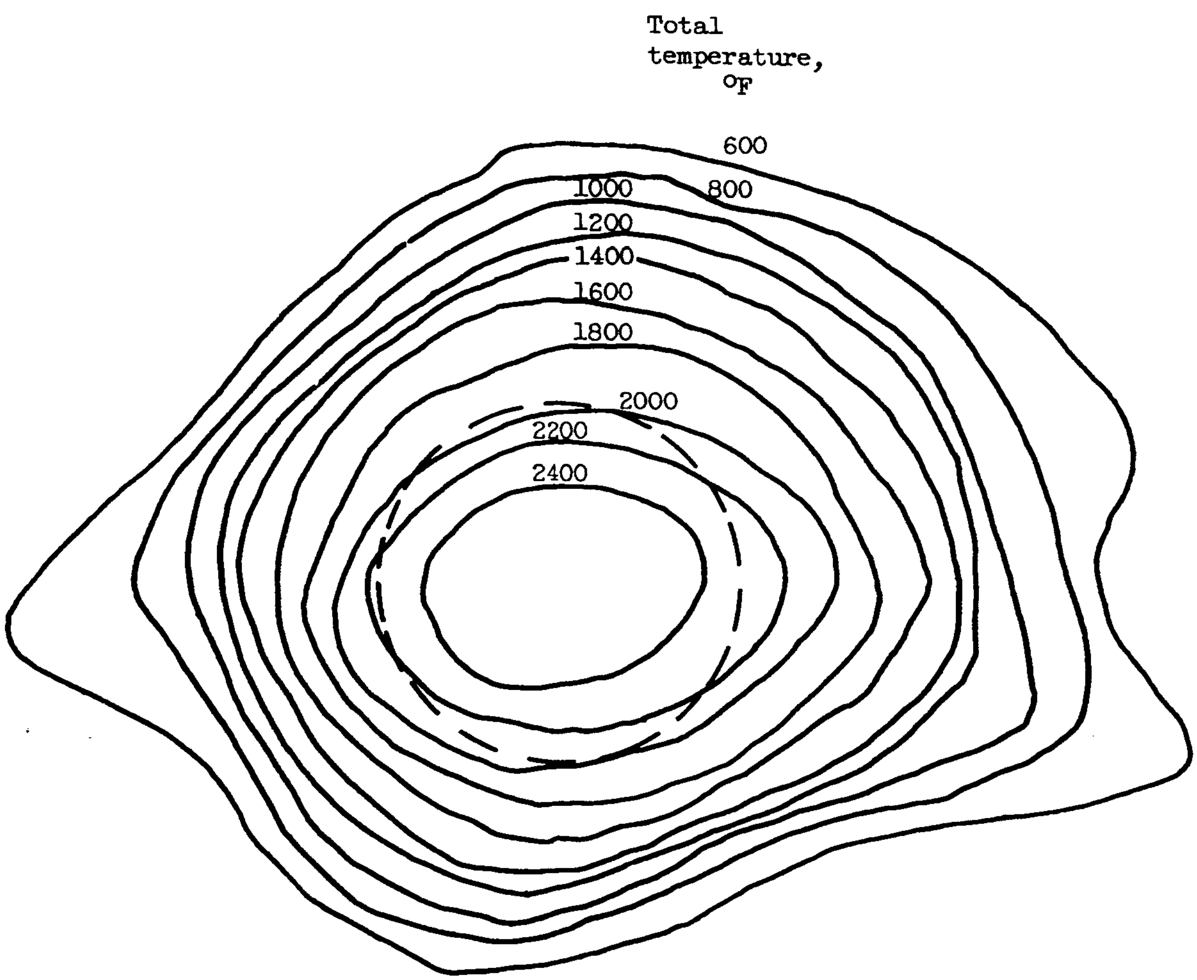


Figure 10. - Combustion stability of several single-element models. Inlet air temperature, 80° F.

[redacted]

[redacted]



E-214

Figure 11. - Typical temperature distribution $10\frac{1}{2}$ inches downstream of single swirl-can combustor (A17). Combustor-inlet pressure, 10.3 inches of mercury absolute; inlet temperature, 90° F; velocity, 110 feet per second; fuel flow, 10.7 pounds per hour.

[redacted]

[redacted]

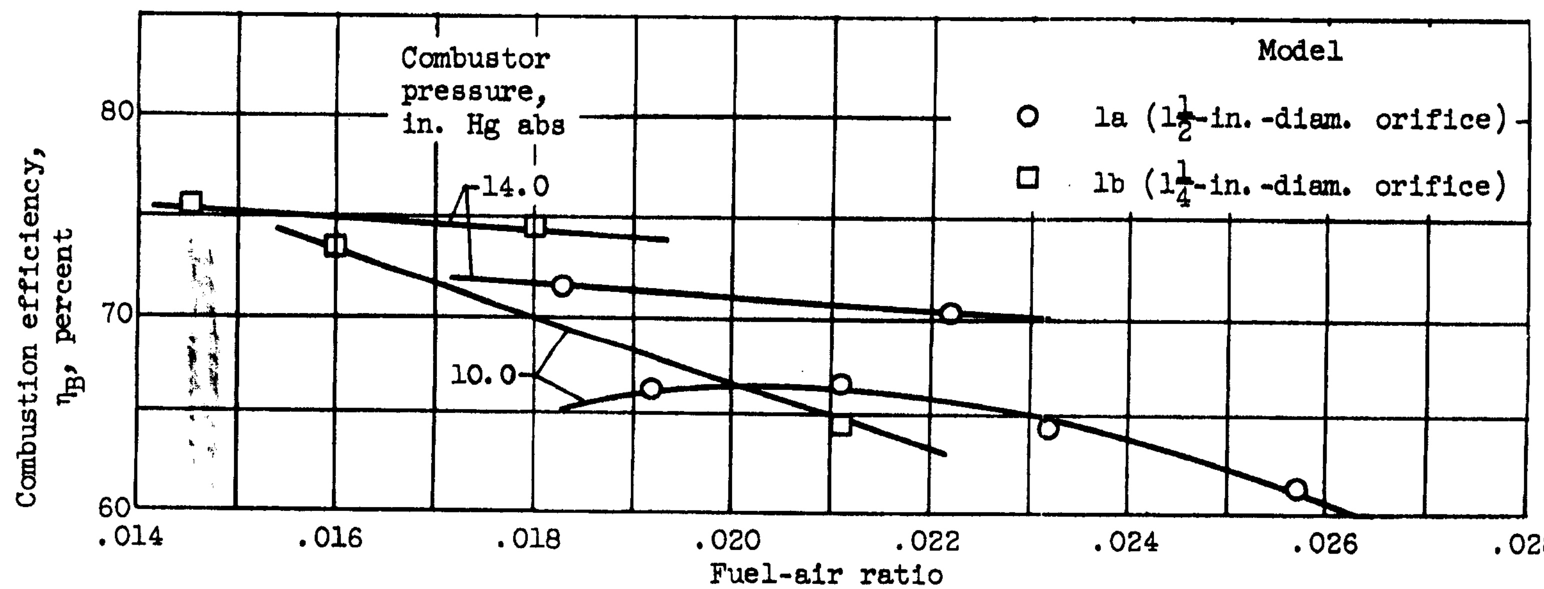


Figure 12. - Combustion efficiency of model 1 with varying inlet diameter orifices. Inlet air temperature, 350° F; reference velocity, 75 feet per second.

[redacted]

[illegible]

[illegible]

[redacted]

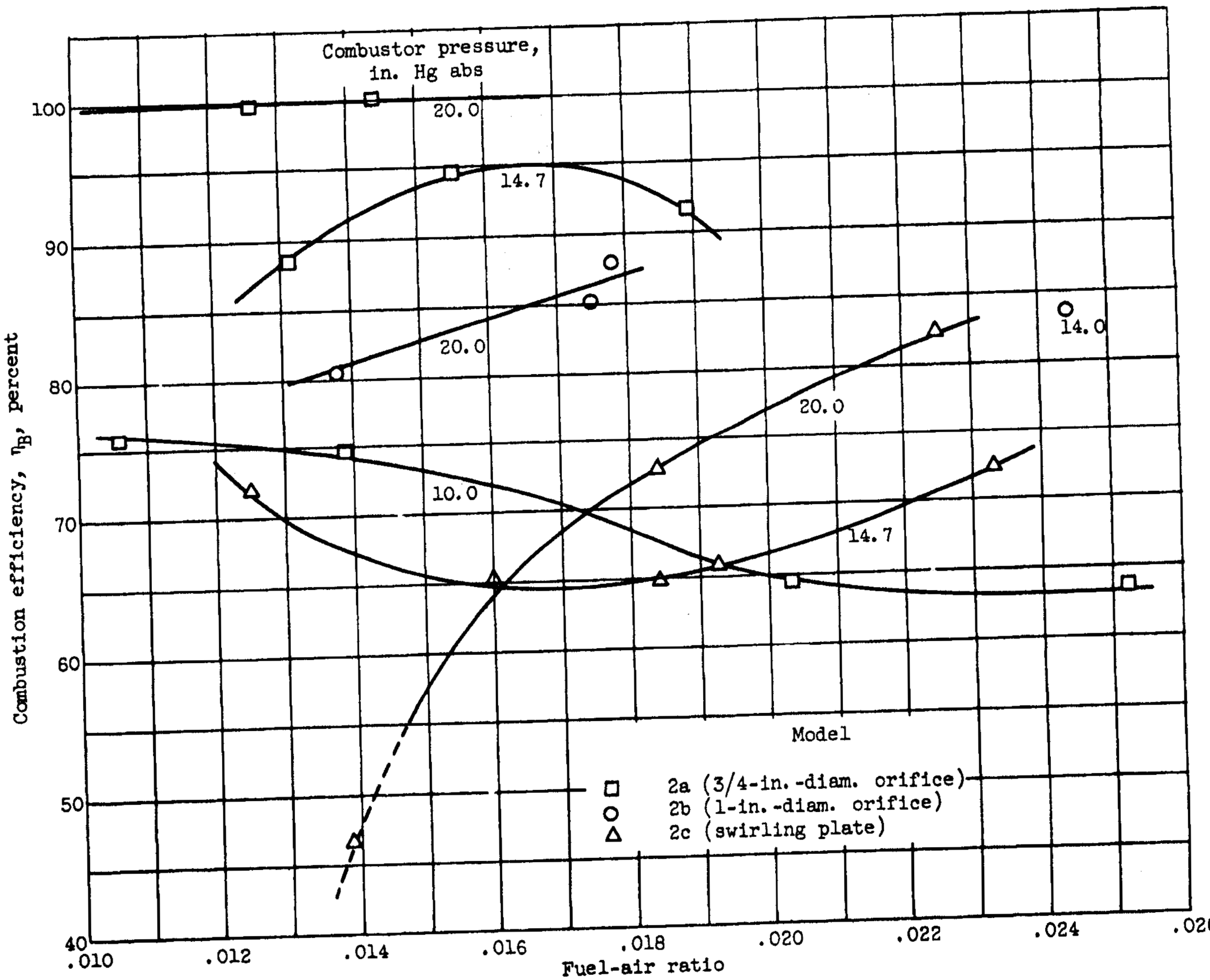


Figure 13. - Combustion efficiency of model 2 with different inlets. Inlet air temperature, 350° F; reference velocity, 75 feet per second.

[redacted]

[illegible]

[illegible]

[redacted]

E-214

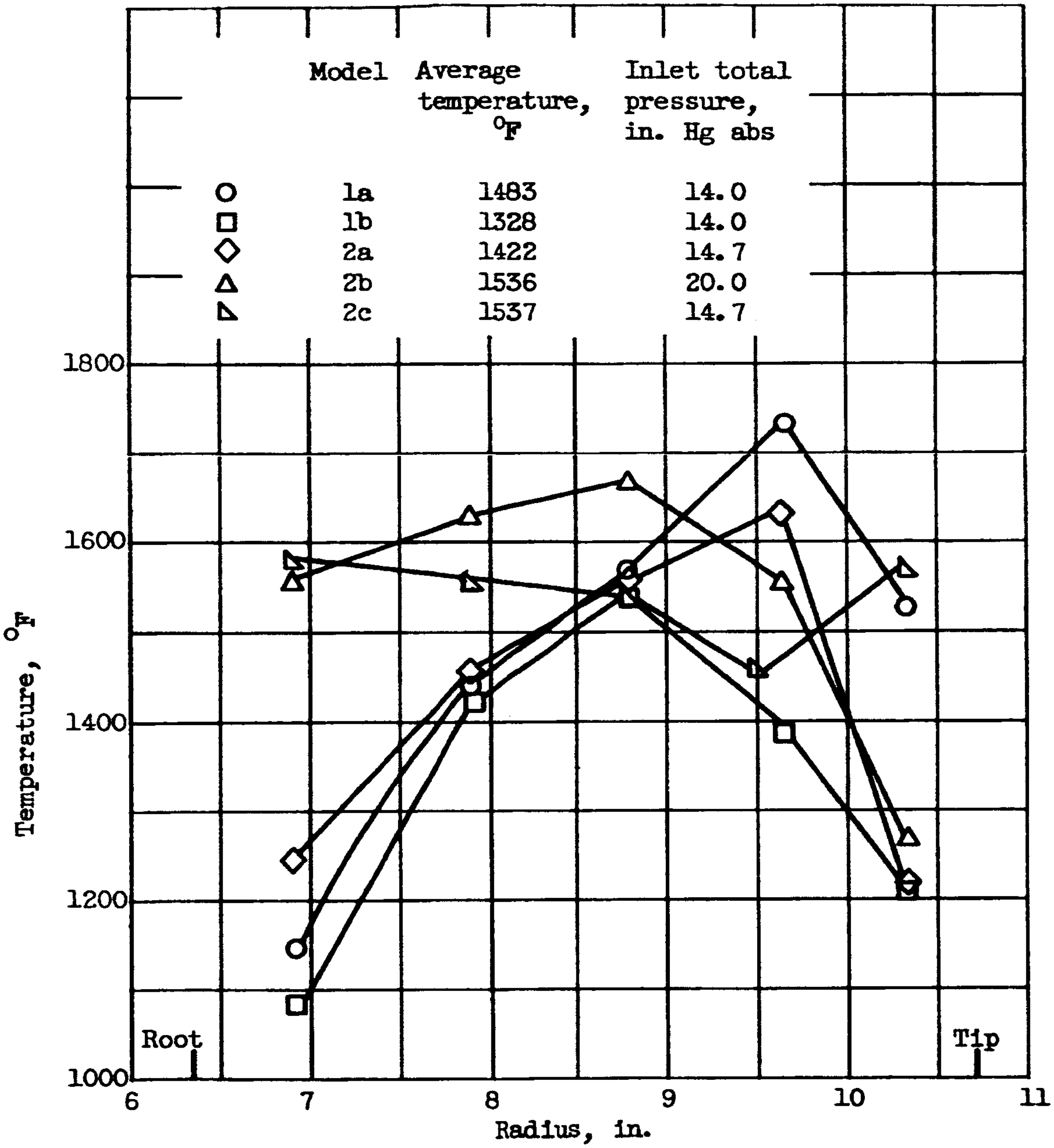


Figure 14. - Comparison of combustor-outlet temperature profiles. Inlet temperature, 350° F; reference velocity, 75 feet per second.

[redacted]

[redacted]

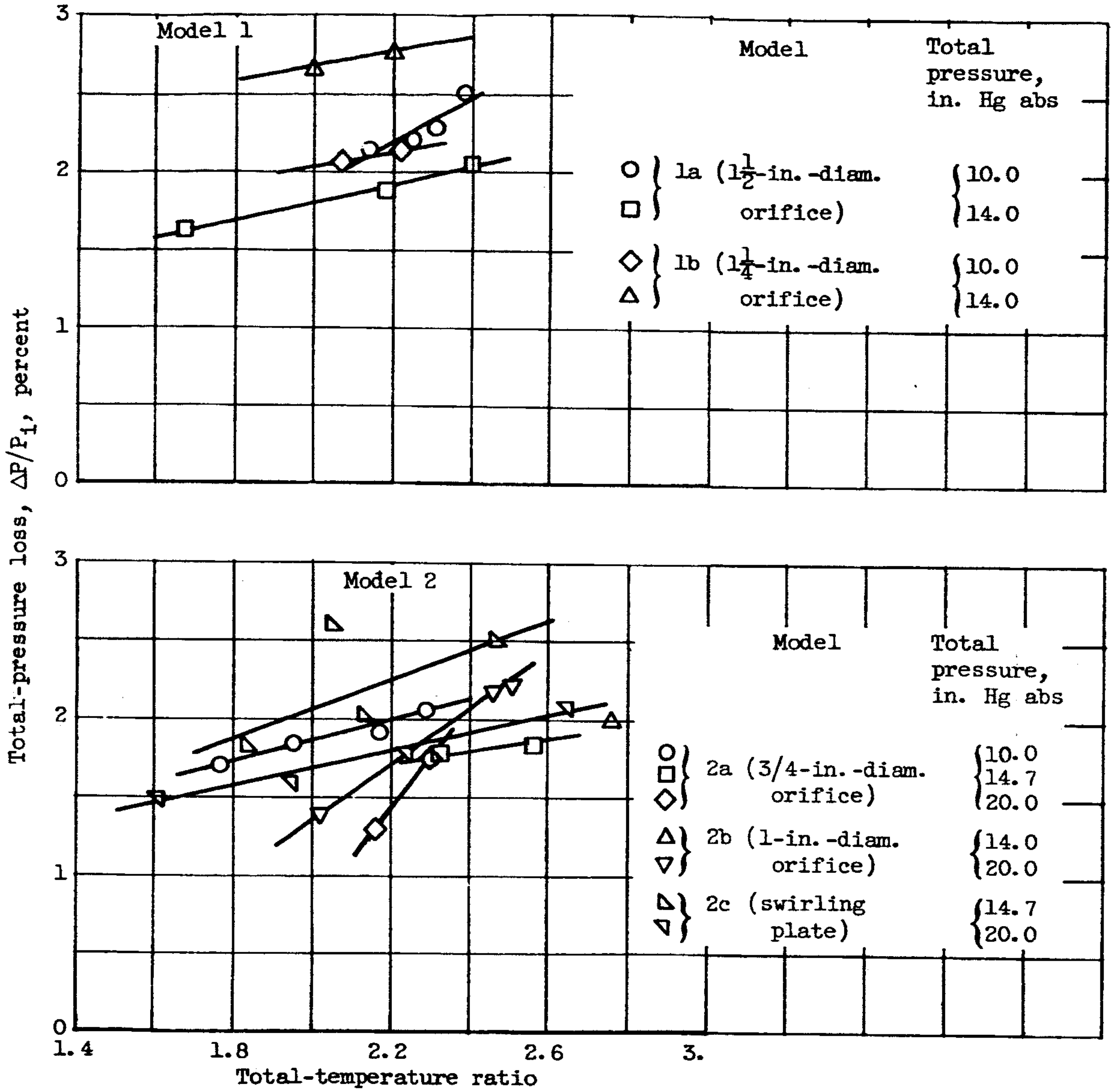


Figure 15. - Total-pressure loss for models 1 and 2. Inlet air temperature, 350° F; reference velocity, 75 feet per second.

[redacted]

[redacted]

[redacted]